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Performance and Air Pollutant Emissions of an Experimental Water/Residual Oil Emulsion Burner in a Commercial Boiler

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16. ABSTRACT The paper presents the performance and air pollutant emissions of an experimental water/oil emulsion burner. The burner was fired with two residual oils at selected emulsion water fractions. In addition, various stoichiometric ratios and two load conditions were used to determine how operational parameters influenced the results. Particulate mass emissions and particle size distributions are presented. Examples show that, even though particulate mass may decrease, the total amount of fine particulate emissions may increase by using water/oil emulsions. The performance of the boiler is reduced when large fractions of water are used in the emulsion due to latent heat losses. This performance loss may be only slightly recovered by operating at a reduced stoichiometric ratio corresponding to a smoke limit. NOx and CO emissions data are also presented for various test conditions, but neither were affected significantly by use of water/oil emulsions.

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Residual Oils	Boilers	Stationary Sources	21D	13A
Emulsions		Water/Oil Emulsions	07D	
Combustion		Particulate	21B	
Dust			11G	
Aerosols				
Nitrogen Oxides			07B	

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Performance and Air Pollutant Emissions of an Experimental Water/Residual Oil Emulsion Burner in a Commercial Boiler

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The performance and air pollution emissions of an experimental water/oil emulsion burner are presented. The burner was fired with two residual oils at selected emulsion water fractions. In addition, various stoichiometric ratios and two load conditions were used to determine how operational parameters influenced the results. Particulate mass emissions and particle size distributions are presented. Examples show that, even though particulate mass may decrease, the total amount of fine particulate emissions may increase by using water/oil emulsions. The performance of the boiler is reduced when large fractions of water are used in the emulsion due to latent heat losses. This performance loss may be only slightly recovered by operating at a reduced stoichiometric ratio corresponding to a smoke limit. NO_x and CO emissions data are also presented for various test conditions, but neither were affected significantly by use of water/oil emulsions.

Introduction

The performance and environmental effects of water/oil emulsions fired in special burners have been shown to be influenced by the fuel, equipment design, and operating parameters [1-8]. In order to obtain technical information about oil and water/oil emulsions, the U.S. Environmental Protection Agency's Industrial Environmental Research Laboratory in Research Triangle Park, N.C., has established an ongoing in-house experimental program. The research presented in this paper was conducted as part of that experimental program.

Early reports on burning emulsions of oil and water were that emulsions burn faster, improve combustion, and reduce soot formation in comparison to conventional oil combustion [1]. In the late 1960's, Barrett, et al., [2] of Battelle-Columbus Laboratories performed preliminary tests of water/oil emulsions under contract to the U.S. Public Health Service, one of EPA's predecessors. Scherer and Tranie [3] reported test results in which particulate mass was carefully measured, but few data were obtained for other emissions, and no efficiency data were obtained. Turner and Siegmund showed that emulsions reduce thermally generated NO_x, but do not influence NO_x formed from fuel nitrogen [4]. Also, Dryer has reviewed information on combustion of emulsions from a variety of sources [5,6].

More recently, Hall reported results for commercial boilers comparing the Total and Cottell Reactor water/oil emulsifiers with conventional distillate and residual oil firing at similar stoichiometric ratios [7,8]. He presented four applications where emulsions caused the particulate emissions to be reduced and showed that smoke and CO emissions may be increased or reduced, depending on fuel, equipment, and operation. NO emissions were reduced while firing distillate oil but were not significantly affected when residual oil was fired. The indicated changes in efficiency due to firing emulsions were also found to vary (from an increase of about 1 percent to a reduction of about 7 percent) in comparison to firing only oil, with the excess air being set for a smoke limit in both cases.

Elf Union, a French national petroleum company, in cooperation with SICMA, a European burner manufacturer, has developed various high pressure atomizing emulsion burners. These have been installed for commercial and industrial heating applications and for petroleum waste incineration. In 1971 preliminary tests were conducted in France jointly by Elf Union and one of EPA's predecessors, the U.S. National Air Pollution Control Administration [9]. The results indicated that NO_x emissions were increased with load and did not depend on whether a water/oil emulsion or only oil was fired. However, at high load with high stoichiometric ratios, firing an emulsion resulted in a slight increase of NO. Operation at lower than normal stoichiometric ratios was possible without encountering flame instability or high particulate levels when the emulsion was used. This capability, coupled with the trend of a decrease of NO_x with decreased excess air, pointed to the possibility of some reduction of NO_x by the use of emulsions.

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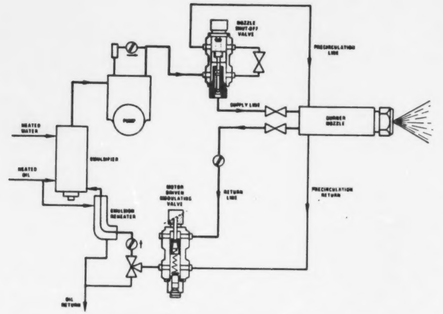

Fig. 1 Elf/SICMA experimental water/oil emulsion burner system

A decision was made to purchase and test an experimental Elf/SICMA emulsion burner modified for variable emulsion and combustion conditions. The objectives were to determine the influence of water fraction, stoichiometric ratio, and oil firing rate on burner performance and on gaseous and particulate emissions.

Burner and Test Description

The experimental Elf/SICMA emulsion burner was designed for return flow modulated firing of both distillate and residual oils. A schematic diagram of the burner system is shown in Fig. 1. The designed oil firing rates were variable from around 0.038 to 0.227 m^3/hr (10 to 60 gph) by the use of different burner nozzles, blast tubes, and air handling components. According to the manufacturer, the emulsion water should be limited to 30 percent of the volume flow rate of a residual oil or 15 percent of a distillate oil. The burner port and air intake were modified for experimentally controlled firing in an available North American packaged Scotch boiler rated at 0.73 MW (2.5×10^6 Btu/hr).

Tests were conducted with a residual fuel oil fired at intermediate (0.045 m^3/hr or 12 gph) and high (0.064 m^3/hr or 17 gph) load conditions. Water fractions in the emulsion were varied from zero to 0.38 kg water/kg fuel in order to determine the influence of the amount of water on performance and pollutant emissions. Combustion air was controlled for stoichiometric ratios between 1.1 and 2.0 in order to determine the characteristics associated with reduced excess air operation. Most of the results were obtained with 21.8° API fuel oil, but some results were obtained with 19.2° API oil. The properties of these oils are presented in Table 1. Unless specified as data obtained from tests with 19.2° API oil, data discussed in this report and shown in the figures were obtained from tests with 21.8° API oil.

Operating Experience

Typical burner testing include a 2 hr warmup period. After each test condition change, at least 30 min of stable combustion were required before data were taken. Approximately 10 min were required for each test where only gaseous and smoke emissions were measured. One hour of sampling was required for total particulate mass and particulate size test. During the test program the unit was operated approximately 500 hrs.

Combustion stability became a problem only at the higher firing rate when using the upper limit of emulsion water regardless of the stoichiometric ratio. This may have been the result of the nozzle being too small for the flow rate of the emulsified fuel or it may have simply been a result of too much water.

Test Measurements

During each typical test run, data were manually recorded for the following physical parameters: fuel flow rate; emulsion water flow rate; various oil and water pressures and temperatures; stack temperature; ambient air temperature; barometric pressure; condenser cooling water temperatures; and orifice pressure differences.

Gaseous emissions were measured with the following continuous analyzers:

Gas	Analyzer
Oxygen (O_2)	Paramagnetic
Carbon Dioxide (CO_2)	Nondispersive Infrared (NDIR)
Carbon Monoxide (CO)	Nondispersive Infrared (NDIR)
Nitric Oxide (NO)	Chemiluminescence
Hydrocarbon (HC)	Flame Ionization

It should be noted that an unheated sampling line was used. Therefore, NO_2 data could not be obtained and hydrocarbon data may be artifically low.

Smoke was measured under steady state operating conditions and a Bacharach smoke spot number was obtained by averaging ten smoke spots taken at 1 minute intervals [10].

Total particulate emissions were determined for selected test conditions using the EPA Method 5 testing procedure. A minimum of two samples were collected at each test condition.

Table 1 Properties of residual fuel oils used

Parameter			
API (deg		21.8	19.2
Carbon (percent)		86.9	86.9
Hydrogen (percent)		12.2	11.85
Nitrogen (percent)		<0.10	<0.10
Ash (percent)		0.04	0.05
Sulfur (percent)		1.02	1.10
Heat of Combustion			
Gross	(Btu/lb)	18,981	18,879*
	(MJ/kg)	44.150	43.912*
Net	(Btu/lb)	17,868	
	(MJ/kg)	41.560	
Density			
311 K			
(100°F)	(g/cm^3)	0.9086	
	(kg/m^3)	908.6	
372 K			
(210°F)	(g/cm^3)	0.8699	0.8858*
	(kg/m^3)	869.9	885.8*
Viscosity (cp or mPa)			
311 K			
(100°F)		80.77	
372 K			
(210°F)		8.99	

*Best estimate.

Particulate size distributions were determined by using the Mark III Andersen Stack Sampler. A minimum of two Andersen samples were obtained at each selected test condition. A microcomputer with an EPA program providing correction coefficients was used to obtain cumulative mass fractions corresponding to aerodynamic particle diameters [11].

In addition, data were obtained for an EPA Level 1 Environmental Assessment [12]. This required the use of a Source Assessment Sampling System (SASS) Train with subsequent data reduction by Battelle-Columbus Laboratories [13]. The analysis included: spark source mass spectroscopy to provide inorganic particulate information; atomic absorption spectroscopy to provide data about the emission of mercury (Hg), arsenic (As), and antimony (Sb); and total chromatographable organic analysis, gravimetric analysis, infrared analysis, and low resolution mass spectroscopic analysis to obtain information about organic emissions.

Performance Evaluation

The relative performance of the boiler at various emulsion test conditions can be evaluated by either measuring the energy released in a steam condenser or computing energy losses to the boiler room and up the stack [14]. Because of a lack of precision in the available test measurments at the

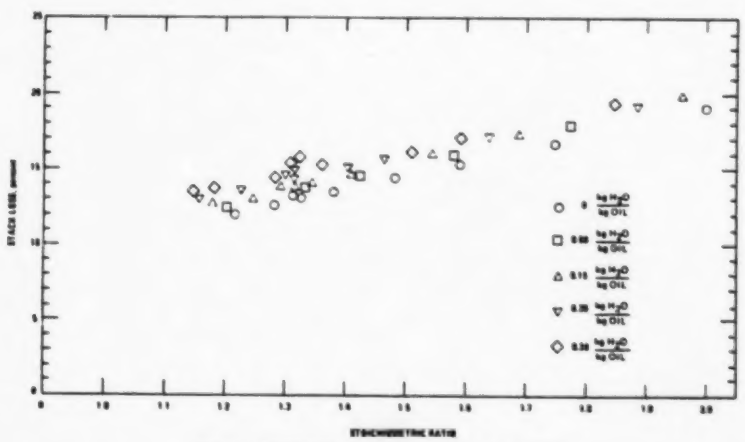

Fig. 2 Stack losses at intermediate firing rate

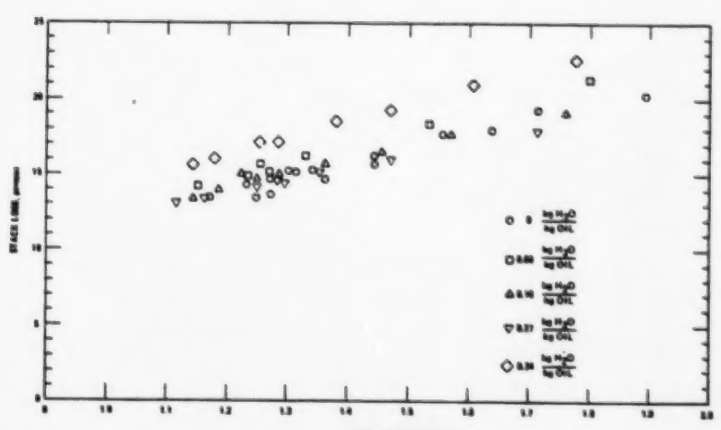

Fig. 3 Stack losses at high firing rate

condenser, the energy loss method was selected. It was assumed that the energy loss to the boiler room did not vary significantly and that stack loss was the major energy loss variable.

Latent and sensible flue gas stack losses were conveniently computed using a programmable calculator. Included were the intermediate calculations to determine the oil and water flow rates, the net stack gas temperature, the amounts of major component flue gases, and the average flue gas specific heat.

The performance results are shown in Figs. 2 and 3 as stack losses corresponding to the intermediate (0.045 m^3/hr or 12 gph) and high (0.064 m^3/hr or 17 gph) oil firing rates, respectively. Although there is some scatter in the data, the results show the expected trend of reduced stack losses associated with reduced stoichiometric ratio. Increased stack losses for increased amounts of emulsion water are caused by the greater latent heat losses. From a combustion efficiency standpoint, it is interesting to note that for the current test program good combustion energy release occurs, and very little energy loss is associated with production of carbon particulate and carbon monoxide.

Particulate Emissions

The averaged total particulate mass emissions are presented in Fig. 4. With one exception, the tests showed less total particulate emissions when an emulsion was fired than when only oil was fired. Although considerable scatter was noticed (up to 22 percent), the averaged results showed an increased total particulate mass emitted only when an emulsion having 0.09 kg water/kg fuel was used at the higher firing rate.

Figure 4 shows that as the amount of emulsion water increased the total particulate emissions generally decreased. The results also indicate that less particulates (on a normalized basis) are emitted at the higher firing rates, except when the unit operates at the upper limit of water in the emulsion. For either firing rate at high values of water in emulsion, the particulates appear to approach a lower limited value (around 42 mg/m^3). This value is only 20 percent higher than the anticipated particulate emissions from the fuel ash alone without any combustibles. Consequently, at the high water emulsion values, the carbon burn-out is very good.

When the burner was fired with the heavier API 19.2° oil in comparison with the API 21.8° oil, total particulate mass emissions were greater at any given water-to-oil ratio. This was probably caused by the poorer atomization quality of the heavier oil. Note that a modest amount of emulsion water had a greater impact on reducing particulate emissions for the heavier oil than for the lighter API 21.8° oil.

The cumulative particulate size distributions are shown for the intermediate and high firing rates in Figs. 5 and 6, respectively. The emulsion causes smaller particulates to be emitted. This is probably due to improved secondary atomization. Figure 5 shows that, at the intermediate flow rate, an increase of the amount of water causes a general reduction in particulate sizes. Although some overlaying of the results is found at the higher firing rate (Fig. 6), the trend is generally established. Both figures also confirm that the average particulate sizes are larger for the heavier API 19.2° oil than for the API 21.8° oil.

It is important to note that the fractions of fine particulates (less than 2.5 μm) from emulsions may be significant. Consider the example of the API 21.8° oil at the higher firing rate. The fraction less than 2.5 μm is 63 percent for the emulsion with 0.34 kg water/kg oil, compared to about 42 percent when firing oil only. From Fig. 4, the total particulate emissions were 46.5 mg/m^3 at the high water emulsion value compared with 70 mg/m^3 with only oil being fired. Therefore, about 29.3 mg/m^3 of particulates smaller than 2.5 μm were emitted with either the high water emulsion or only oil being fired. Thus, the mass of fine particulates remained constant even though the percentage increased when firing an emulsion. On the other hand, when the heavier oil (API 19.2°) was fired at the intermediate rate, more fine particulates were emitted with the emulsion than for firing oil only.

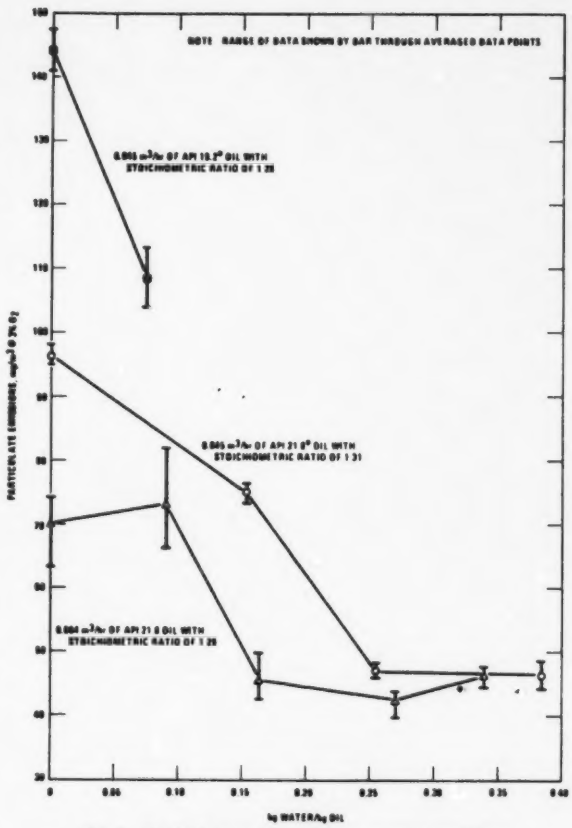
NOTE: RANGE OF DATA SHOWN BY BAR THROUGH AVERAGED DATA POINTS
0.045 m³/hr OF API 19.2° OIL WITH STOICHIOMETRIC RATIO OF 1.28
0.045 m³/hr OF API 21.8° OIL WITH STOICHIOMETRIC RATIO OF 1.31
0.064 m³/hr OF API 21.8 OIL WITH STOICHIOMETRIC RATIO OF 1.25
PARTICULATE EMISSIONS, mg/m³ @ 3% O₂
kg WATER/kg OIL

Fig. 4 Particulate emissions from various emulsions

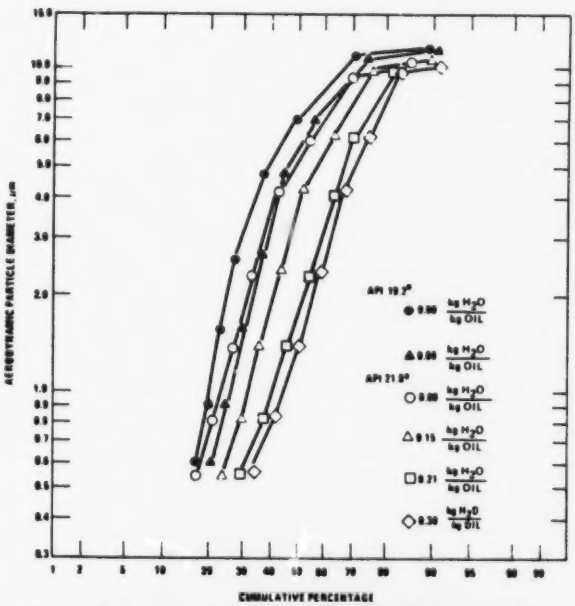

Fig. 5 Particulate size distribution for intermediate firing rate

The data indicate that in all cases considerably more than 99 percent of the particulate emitted was in the inhalable size range (defined as less than 15 μm).

Smoke Emissions

The smoke emissions are presented as Bacharach smoke spot numbers for the intermediate and high firing rates in Figs. 7 and 8, respectively. Both figures show that low smoke is associated with firing only oil. As the water fraction in the emulsion is increased to moderate levels, the smoke increases; and as the water fraction increases to the upper limit, the smoke is generally reduced to below that corresponding to only oil being fired. The influence of reduced stoichiometric ratio is to increase smoke, as is typical for conventional oil burners. For residual oil burners, the useful practice is to operate near a limiting Bacharach smoke number of 3 or 4, depending on the grade of oil being fired. Such a limiting value is recommended as being acceptable from the perspective of both efficiency and emissions [15].

There appears to be a modest advantage for high water fraction emulsions in terms of operation at lower stoichiometric ratios at a smoke limit. However, in consideration of the stack loss results (Figs. 2 and 3), a decrease in efficiency will generally result.

It is interesting to note that as the load is decreased to the intermediate firing rate the smoke emissions increase. This is probably associated with lower furnace temperatures and poorer air/fuel mixing (due to lower air velocities) at the lower firing rate.

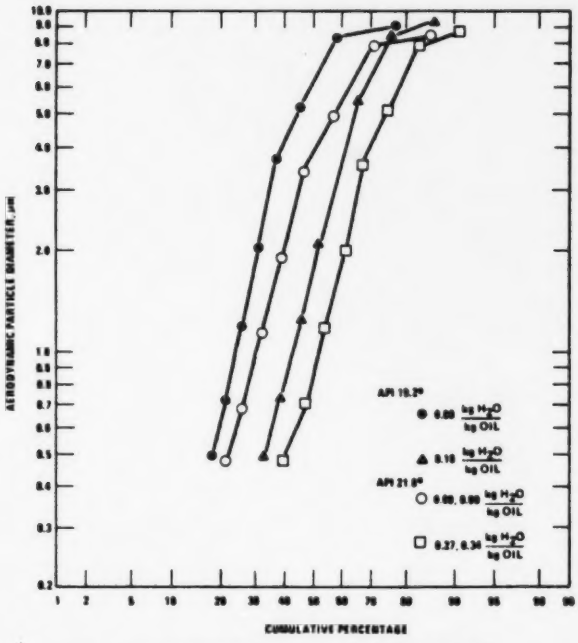

Fig. 6 Particulate size distribution for high firing rate

Nitric Oxide Emissions

The nitric oxide, NO, emissions corresponding to the intermediate and high firing rates are presented in Figs. 9 and 10, respectively. As expected, NO emissions are reduced at lower stoichiometric ratios. They are also higher at the higher firing rate, probably as a result of higher combustion temperatures.

At the intermediate firing rate, the emulsion caused greater NO emissions when the stoichiometric ratio exceeded 1.4. Below a stoichiometric ratio of 1.4, it appears that NO emissions are reduced by firing higher water emulsions.

At the higher firing rate a slight increase in NO emissions is observed for emulsions with 0.16 and 0.27 kg water/kg oil in comparison to firing with only oil. This behavior probably results from an increased combustion temperature associated with better atomization up to these water/oil ratios. However, as the amount of water in the emulsion was increased to 0.34 kg water/kg oil, less NO was emitted than in the case where only oil was fired. This behavior probably results from the latent heat of water at this high rate reducing combustion temperatures, and thus reducing thermal NO formation. This

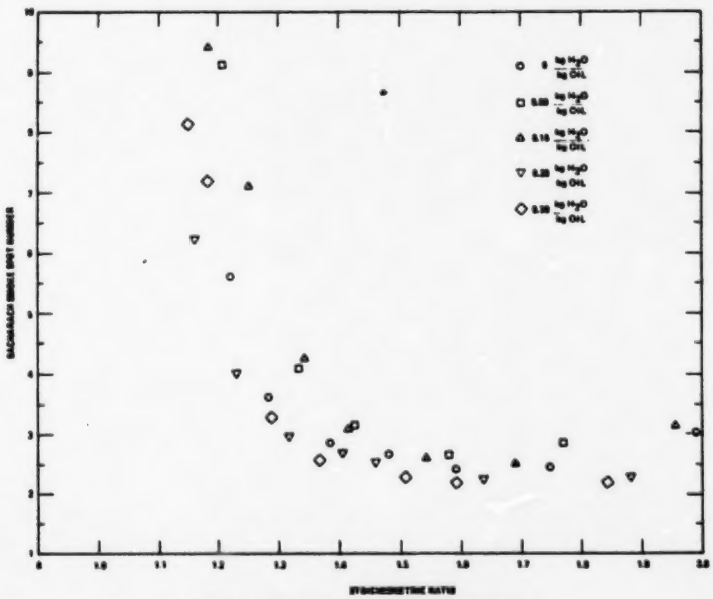

Fig. 7 Smoke at intermediate firing rate

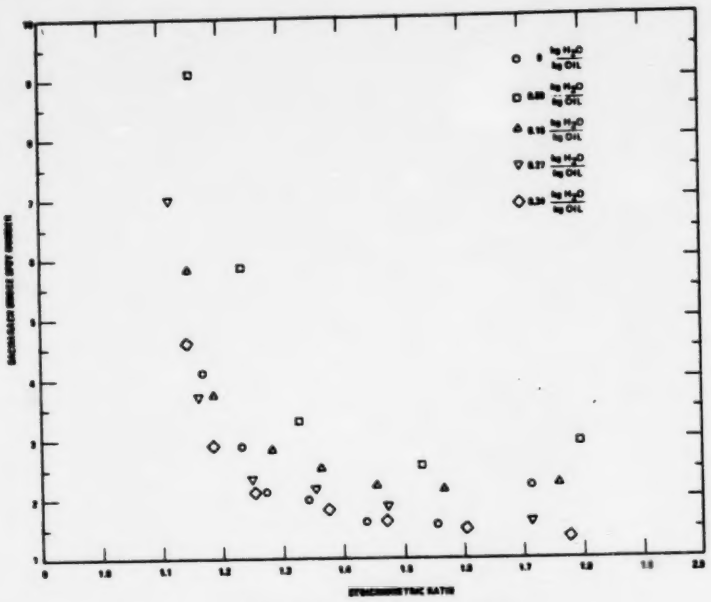

Fig. 8 Smoke at High firing rate

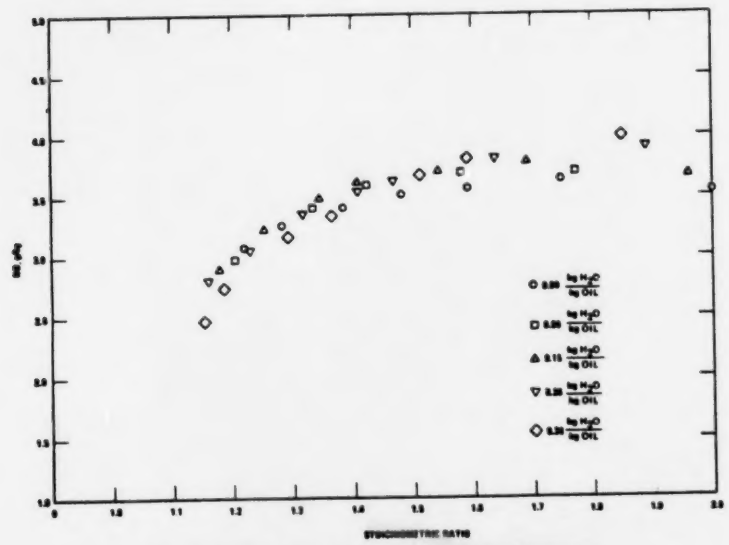

Fig. 9 Nitric oxide emissions at intermediate firing rate

could also explain the similar behavior noted at the intermediate firing rate for stoichiometric ratios below 1.4.

It should be noted that NO emissions are directly related to fuel nitrogen content. The nitrogen content of both fuels used in this study was relatively low for residual fuel oil.

Carbon Monoxide and Hydrocarbon Emissions

Emissions of carbon monoxide, CO, were found to be very low (less than 0.4 g/kg oil, or 30 ppm at 3 percent O_2) for all cases except for low stoichiometric ratios. The measured increase of CO at low stoichiometric ratios, as shown in Figs. 11 and 12, is consistent with accepted combustion theory [15]. Hydrocarbons were measured but were not detected under any conditions. As mentioned previously, this may be due to the unheated sampling line.

Trace Specie Emissions

Samples collected by the Source Assessment Sampling System (SASS) train, while firing the 0.26 kg water/kg oil emulsion at the high firing rate and while firing oil only at the high firing rate, were analyzed for trace species. The samples were analyzed by procedures as specified in reference [12]. Detailed results of the analysis are given in reference [13].

The only significant differences between the two samples occurred in the organic material analyses, as shown in Fig. 13. The general trend is that the fuel oil along emitted about 25 percent more material than the emulsion burner. However, fractions 3 and 4 deviate significantly from this trend. In fraction 3 the trend is completely reversed, with the emulsion burner emitting about twice as much as the fuel oil burner. This is significant since fraction 3 can contain species such as

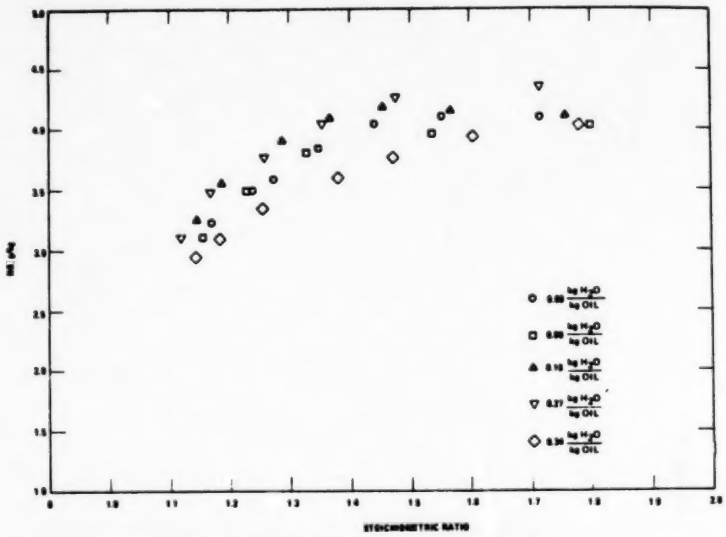

Fig. 10 Nitric oxide emissions at high firing rate

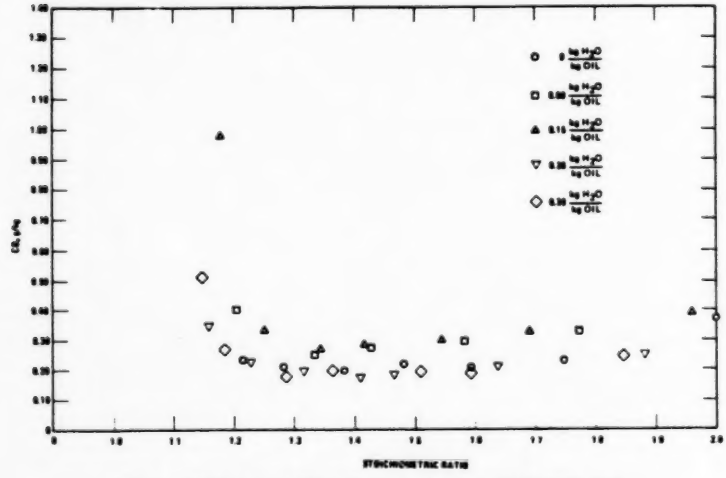

Fig. 11 Carbon monoxide emissions at intermediate firing rate

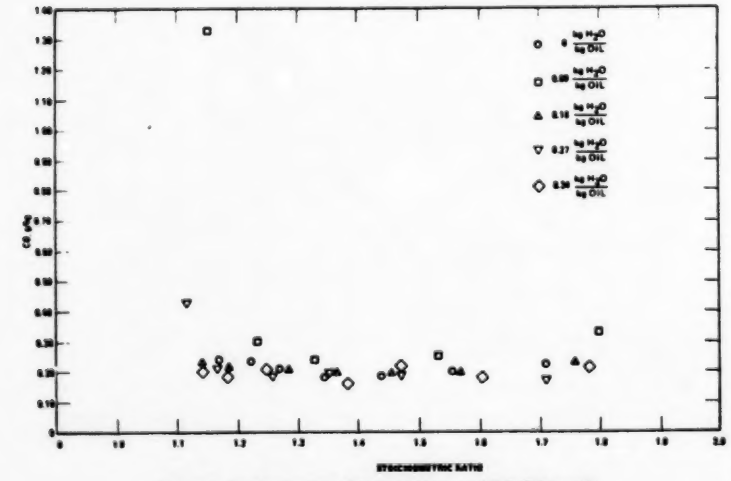

Fig. 12 Carbon monoxide emissions at high firing rate

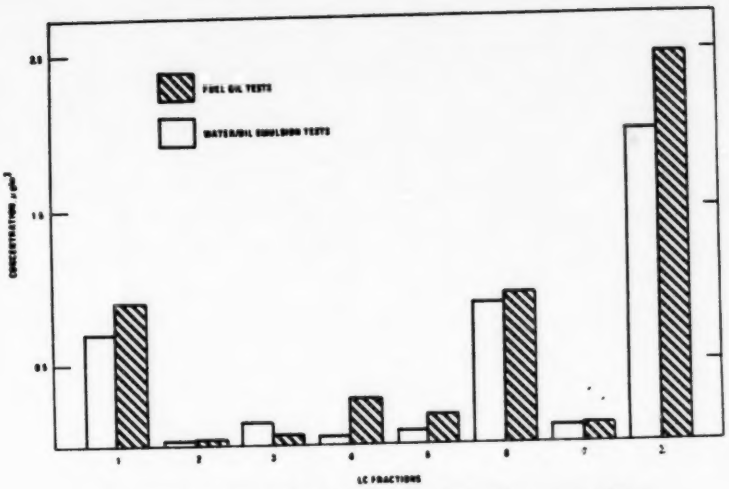

Fig. 13 Comparison of liquid chromotography fraction concentrations at the source

benzo(a)pyrene, which is hazardous in very low concentration. On the other hand, fraction 4 shows that the fuel oil test emitted seven times as much material as the emulsion test. However, this fraction does not contain materials which are hazardous in low concentration.

For these reasons, the total degree of hazard for the emissions from the emulsion fuel is approximately twice that of the fuel oil emissions, as reported in reference [13]. This is due almost entirely to the previously mentioned result that the liquid chromatography fraction 3 concentration for the emulsion is about twice that of the fuel oil test. Since the analysis performed did not isolate specific organic compounds in fraction 3, a more detailed analysis would be necessary in order to reach definite conclusions.

Conclusions

1 As the amount of water in the emulsion is increased, the boiler performance is shown to decrease due to increased latent heat loss. As with other burners, the stack losses are reduced at lower stoichiometric ratios, up to a smoke or particulate emission operational limit. The increased stack losses associated with higher water ratios in the emulsified fuel are not significantly offset by operating at lower stoichiometric ratios.

2 Total particulate mass emissions were generally found to be reduced with the use of water/fuel emulsions in comparison to burner operation with oil only. Also, as more water was added, the average amount of particulate mass emissions was generally reduced, although some small increases were observed at the high firing rate.

3 Particulate size distributions, as measured by the Andersen Stack Sampler, showed reproducible trends of increased fractions of small particulates and reduced fractions of large particulates as the water fraction in the emulsion was increased. In addition, the mass of fine particulates (less than 2.5 μm) emitted may be increased by using water/oil emulsions compared to firing only oil.

4 Total particulate emissions were found to increase by switching from a 21.8° to a heavier 19.2° API residual fuel oil. The average particle size was found to increase with the heavier oil.

5 Except for the highest water/oil ratios, smoke levels increased when emulsions were fired compared to only oil being fired.

6 As with other oil burners, the normalized emissions of NO generally were found to increase with increased load and with increased stoichiometric ratio.

7 There was not a significant change in NO emissions for any emulsion at the intermediate firing rate and for the lowest water/oil emulsion ratio at the high firing rate. However, at the high firing rate NO emissions did increase somewhat with emulsions of 0.16 and 0.27 kg water/kg oil. For the highest water/oil emulsion ratio tested, 0.34 kg water/kg oil, NO emissions were decreased by as much as 8 percent compared to firing oil only.

8 Burner stability became a problem only when firing at the highest water/oil emulsion flow rate. This is probably because the flow exceeded the design capacity of the nozzle, or because there was too much water in the emulsion for good combustion.

Acknowledgments

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